RM-76-79

THE IMPACT OF WASTE HEAT RELEASE ON SIMULATED GLOBAL CLIMATE

A.H. Murphy[1], A. Gilchrist[2], W. Häfele,
G. Krömer, J. Williams

December 1976

[1] National Center for Atmospheric Research, Boulder, Colarado, USA.

[2] UK Meteorological Office, Bracknell, Berkshire, UK.

PREFACE

The IIASA Energy Program is studying global aspects of energy systems in terms of resources, demands, options, strategies and constraints. One constraint on an energy system is represented by its impact on climate. During the last two years a study of the possible impacts of energy systems on climate has started. This report describes results of a study of the impact of waste heat from large-scale energy parks on the global atmospheric circulation, as simulated by a numerical model. Work will continue with further model experiments which are suggested by the present results.

SUMMARY

The general circulation model of the United Kingdom Meteorological Office (UKMO) has been used to investigate the effects of thermal pollution from large-scale energy parks on climate. Two scenarios, with different locations for the energy parks, have been considered.

Emphasis was placed on finding an estimate of model variability (on the basis of three control cases), so that the significance of the change caused by the heat release could be evaluated.

As far as the model climatology is concerned, significant changes were produced by the energy parks. In addition, the location of the parks influenced the model response. The presently available models do not simulate climate in a completely realistic way so that the results of sensitivity experiments must be interpreted very carefully. At the present stage it can be said that the results call for further investigations.

TABLE OF CONTENTS

The Impact of Waste Heat Release on Simulated Global Climate

1. INTRODUCTION

That the impacts of the large-scale production and consumption of energy on climate may represent an important constraint on future energy systems has been discussed by Weinberg and Hammond (1971), Häfele (1974), SMIC (1971), Schneider and Dennett (1975) and several other authors. For example, it has been suggested that waste heat introduced into the atmosphere in the vicinity of large energy parks may have adverse effects on regional and global, as well as local, climate. It has also been recognized for some time that a greatly increased use of fossil fuels could lead to dramatic increases in the carbon dioxide content of the atmosphere, which could in turn lead to significant changes in global climate. In addition to waste heat and CO_2, other by-products of the process of energy production such as particles, gases and moisture may have important effects on climate in the future. With energy production and consumption increasing even more rapidly than population, it seems particularly important to investigate how these by-products of energy systems might significantly influence the climate.

During the last two years the Energy Program at IIASA has started to study the possible impacts of energy systems on climate. This study involves a comparison of the various energy options in terms of their different influences on climate in the medium and long-term future.

The first step of this research has been to explore the possible climatic effects resulting from the existence of ocean energy parks, from which large amounts of waste heat from power stations would be released into the atmosphere and ocean. Arising out of an agreement reached between the International Institute for Applied Systems Analysis (IIASA) and the UK Meteorological Office in Bracknell (UKMO), a model of the atmospheric general circulation developed at the UKMO has been used to run two waste heat experiments, which had different dispositions of energy parks. Three control cases from the model have also been used for comparison with the energy parks experiments.

The evaluation of these model experiments will be discussed in this report.

2. CLIMATE AND ITS SIMULATION

2.1 Climate

A useful definition of climatic state is given by the US Committee for the Global Atmospheric Research Program (1975) as: ...*the average (together with the variability and other statistics) of the complete set of atmospheric, hydrospheric and cryospheric variables over a specified period of time in a specified domain of the earth-atmosphere system. The time interval is understood to be considerably larger than the life span of individual synoptic weather systems (of the order of several days) and longer than the theoretical time limit over which the behavior of the atmosphere can be locally predicted (of the order of several weeks).*

Usually a time period of 30 years is used for studying climatic state; for example, the January climatic state is determined from thirty January values of each climatic variable. Climate models are generally run to produce one realization of a monthly climatic state, i.e. 30-40 day means of climatic variables are determined from the model.

As indicated in the above definition, the complete climate system consists of five physical components: the atmosphere, oceans, cryosphere, land surface and biomass. The physical processes responsible for climate include those involved in weather, with the main process being the rate at which heat is added to the system from the sun's radiation. The atmosphere and ocean develop winds and currents which transport heat from regions where it is received to regions where there is a thermal energy deficit. Figure 1 illustrates the components of the climate system and processes that link them.

Climate, in contrast to weather, has a connotation of stability. However, records show us that on different geographical and temporal scales, climate has exhibited natural fluctuations. The possible causes of such natural climate changes have been discussed by Lamb (1972), Kellogg and Schneider (1974), and Mason (1976) among others. The physical basis of climate has been studied in detail by the US Committee for the Global Atmospheric Research Program (1975) and by GARP (1975).

Before discussing the possibility of man-induced climatic changes, one must emphasize the complexity and coupled nature of the climate system. Interactions among variables in the system (as in Fig. 1) may act either to amplify anomalies of one of the interacting variables (positive feedback) or damp them (negative feedback). Feedback mechanisms in the climate system have been described by Schneider and Dickinson (1974). As pointed out by GARP (1975), in a system as complex as climate, an anomaly in one part of the system may be expected to trigger a series of changes in other variables, depending on the type, location, and magnitude of the initial anomaly.

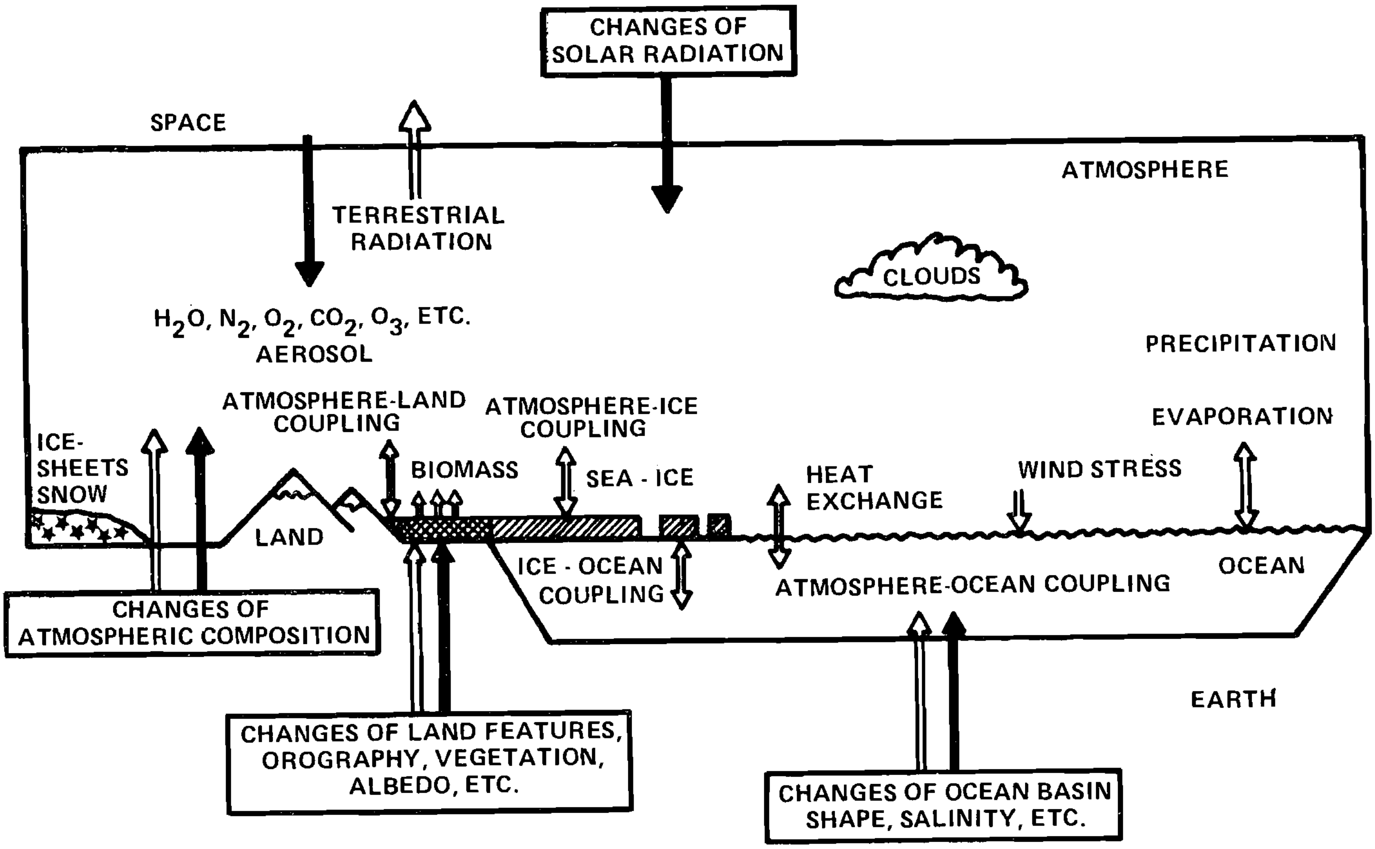


Figure 1. Components of the coupled atmosphere-ocean-land-ice-biomass climatic system. From GARP (1975)

2.2 Nature of GCMs

The processes of the climate system may be expressed in terms of a set of dynamical and thermodynamical equations for the atmosphere, oceans, and ice, together with appropriate equations of state and conservation laws for selected constituents (e.g. water, CO_2 and ozone in the air). These equations describe the processes which determine changes in temperature, velocity, density, and pressure; in addition, processes such as condensation, precipitation, and radiation are considered. The equations can be used to model climate but, because of lack of detailed knowledge of both the observed climate and the methods of computing the processes, various physical and numerical approximations must be made. The system of equations involving those approximations thus becomes a numerical model of climate.

A hierarchy of climate models therefore exists, with each model using different approximations and thus simulating processes on a particular time or space scale. Schneider and

Dickinson (1974) give a detailed description of climate modeling, discussing the hierarchy of models. GARP (1975) and the US Committee for the Global Atmospheric Research Program (1975) also describe the design and use of climate models. Smagorinsky (1974) and Arakawa (1975) have discussed the use of numerical general circulation models (GCM), that is climate models from the detailed end of the hierarchy which simulate the atmospheric circulation. Numerical climate models represent the most promising approach yet available for understanding and predicting climatic change. It is recognized, of course, that the models have several shortcomings. For instance, rather than being joint atmosphere ocean models, most models at present assume that sea-surface temperatures are fixed at appropriate climatological values. Joint atmosphere-ocean models (Manabe and Bryan, 1969; Wetherald and Manabe, 1972) are at an early stage of development. At the present time, also the effect of cloudiness on climate, though potentially very large, is poorly understood and is particularly difficult to represent realistically. Most models, therefore, simplify the treatment of clouds rather drastically. Other simplifications usually made include assuming the values of surface albedos as known and fixed at what are considered from observation to be realistic values.

Despite shortcomings, the models--in particular the GCMs--quite realistically reproduce the basic features of the earth's climate, and so they have been used to study the impact of energy use on climate. They are used to study the response of the simulated atmospheric circulation--which has no feedback to the ocean circulation--to certain boundary conditions. The studies, therefore, essentially solve the equations which govern atmospheric processes to find a climate in equilibrium with certain boundary conditions.

The experiments generally follow a pattern which begins with the specification of the boundary conditions to be used. When studying the effects of waste heat on the simulated atmospheric circulation, we must first specify the amoung of heat that is to be released into the atmosphere and where it is to be released. The complete set of input information to a GCM usually consists of the extent and height of the land surface, the albedos of land surfaces, and the distribution of ocean-surface temperatures; to these we can add changes, for instance, in the heat input or in the amount of atmospheric CO_2.

In summary, there are a number of uncertainties involved in using atmospheric GCMs to assess the possible climatic effects of man-made pollution. No model can claim to reproduce the presently observed climate of the earth with complete fidelity, and the next stage--which is to demonstrate that the models can correctly indicate variations from the present climate due to imposed changes--has barely begun. Work in this field has largely been concerned with sea-surface temperature anomaly experiments in which the model response can be checked against observed significant anomalies. However, the use of GCMs is the only method available that represents non-linear interactions in a realistic way. These interactions must be important if man-made pollution does have significant effects on climate. Therefore, in spite of their shortcomings, the use of GCMs is the most appropriate way now available for investigating such matters. It would, of course, be a mistake to assume that a model necessarily reacts in the same way as the real atmosphere, but any positive response by a model to a realistic level of pollution indicates a possible atmospheric response, which at least calls for further investigation.

3. THERMAL POLLUTION EXPERIMENTS

As pointed out above, some understanding of the response of the atmospheric circulation to thermal pollution has been obtained from the analysis of numerical experiments in which sea-surface temperature anomalies (SSTA) have been introduced. Table 1 gives an overview of SSTA experiments.

Experiments with the UKMO, GFDL, Mintz-Arakawa, and NCAR models have shown several ways in which models respond to sea-surface temperature anomalies. These experiments differ from waste heat experiments in that the heat input to the models from the SSTAs is spread over a larger area than the heat input from thermal pollution. It can be concluded from Table 1 that SSTA experiments have shown that only anomalies in the tropical oceans and unrealistically large anomalies in mid-latitude oceans produce a significant hemispheric response.

Several experiments with GCMs and other models from the lower end of the hierarchy have been conducted to investigate the impact of waste heat on global or hemispheric climate. Washington (1971) used the NCAR general circulation model to investigate the response of the model atmosphere to an addition of 24 Wm^{-2} over all continental and ice regions. This amount of heat is about 100 times the heat energy released over the entire United States during 1965. Results showed a 1-2^{0}C increase in surface temperature with an 8 C^{0}increase over Siberia and northern Canada.

A more realistic input of energy was used by Washington (1972). A per capita energy usage of 15 kW and an ultimate population of 20 billion were assumed (Weinberg and Hammond, 1970), and the thermal pollution was distributed according to population density. Four experiments were made: a control experiment, a thermal pollution experiment, an experiment with the same amount of heat as that added in the thermal pollution experiment but of opposite sign (i.e. negative pollution), and an experiment the same as the control case but with a small initial random error. The temperature differences between the control and positive thermal pollution experiments were as large as 10^{0}C in the northern hemisphere and 1-2^{0}C in the tropics.

Table 1. Sea Surface Temperature Anomaly Experiments

Author and Model	Anomaly	Comments
Rowntree (1972) (GFDL)	Warm and cool anomalies of maximum differences of 3.5^{0}C in tropical eastern Pacific	Tropical and extratropical effects found; Bjerknes (1969) hypothesis is confirmed
Spar (1973a,b,c) (Mintz-Arakawa)	Anomaly of 2-6^{0}C in North Pacific at 22^0-42^{0}N,140^0-180^{0}W Anomaly of 2-6^{0}C in South Pacific at 22^0-42^{0}S,140^0-180^{0}W	Hemispheric and interhemispheric effects noted
Houghton et al.(1974) (NCAR)	Anomaly of 1-2^{0}C in western North Atlantic	Small changes that are difficult to evaluate quantitatively
Gilchrist (1975a) (UKMO)	Anomaly of maximum of 2^{0}C in western Atlantic, off Newfoundland	Consistent effects on surface pressure only near anomaly area
Chervin et al. (1976) (NCAR)	Anomalies with maxima of ±4^{0}C in extratropical North Pacific	Statistically significant response in vicinity of anomalies but no downstream effects
Rowntree (1976) (UKMO)	Anomaly of maximum 2 C in tropical Atlantic, as observed in January 1963	Tropical and extratropical effects found; agreement with observed patterns
Gilchrist (1975b) (UKMO)	Cooling of up to 2^{0}C in tropical Atlantic	Effects on rainfall over Sahara and surface pressure over North Atlantic noted
Shukla (GFDL)	Cold anomaly in Indian Ocean of -3^{0}C	Changes in Indian summer monsoon noted

But the same differences were observed between the control case and the other experiments. It could, therefore, only be concluded that thermal pollution effects were no greater than the noise climatology of the model. These results at least showed how important it is to get an estimate of the natural variability of the model (i.e. noise level) for assessing the significance of a certain difference between a control experiment and anomaly case (that is, for determining the signal to noise ratio). The differences between control cases such as those illustrated by Gilchrist (1975a) for the UKMO model also suggest that it could be misleading to evaluate the energy park experiments against only one control case.

Llewellyn and Washington (1976) discuss a further experiment with the NCAR GCM, in which thermal pollution was added to an area extending from the Atlantic seaboard of the US to the Great Lakes and to Florida. It was assumed that the energy consumption for that region was equal to that presently consumed in Manhattan Island, i.e. 90 Wm^{-2}. Other regions of the globe were not modified. Temperature differences of as much as 12^0C were observed in the vicinity of the anomalous heating but the heating had little effect above the surface layer.

Penner (1976) has used Budyko's global heat balance equation to show that heat addition associated with worldwide energy consumption in the year 2050 would cause a mean global temperature rise of 0.27^0C (0.44^0C between 15^0 and 60^0N), at a 20 kW per capita energy consumption for a world population of 10 billion. With an assumption of 5 kW energy consumption for the same population, the computed temperature rise between 15^0 and 60^0N would be about 0.11^0C and, therefore, not negligible.

Egger (1976) has used a statistical dynamical model of the northern hemisphere to study the effects of thermal pollution. With a distribution of heat input the same as used by Washington (1972), Egger found that the standing waves were not significantly changed. With an input of heat as in IIASA-UKMO experiments (to be described in the next section), the standing waves were changed. With both types of energy input, there was an overall increase of the surface temperature by about 1^0C as well as a slight increase of convective activity.

4. THE IIASA-UKMO EXPERIMENTS

4.1 The UKMO General Circulation Model

The original form of the UK Meteorological Office general circulation model (UKMO GCM) is described by Corby et al. (1972). It represents the global atmosphere by five levels spanning the troposphere and lower stratosphere, with 4626 gridpoints at each level. The vertical levels are equally spaced in terms of pressure at sigma values of 0.9, 0.7, 0.5, 0.3 and 0.1 (sigma value = pressure/surface pressure).

It should also be noted that a hemispheric version of the model was used for the IIASA experiments. Figure 2 shows the distribution of the 2313 gridpoints. The gridpoints are nearly evenly distributed (gridlength is approximately 330 km) at each level, providing sufficient resolution to represent satisfactorily the thermal and dynamical structure of the atmosphere and details of the larger transient weather systems such as the depressions of middle latitudes.

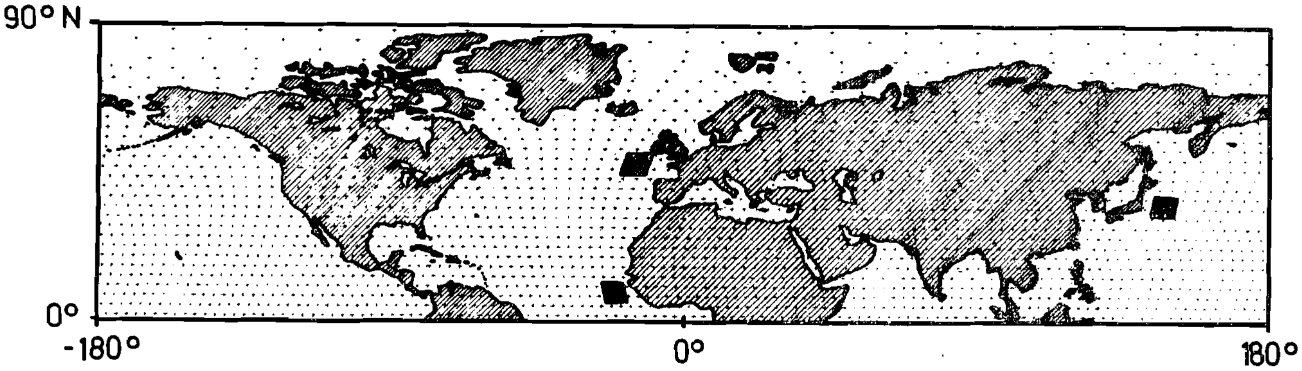


Figure 2. Horizontal distribution of grid points in UKMO model

Prescribed boundary conditions include the earth's orography, the incoming solar radiation and the sea-surface temperatures, which are fixed at seasonal average values. The temperatures of the land surfaces are computed from a surface heat balance equation. A simplified hydrological cycle is considered, in which condensation is assumed to occur when the relative humidity of the air exceeds 100%. The condensed water vapor falls out as rain, and allowance is made for evaporation if the precipitation falls through unsaturated air. The effects of the release of latent heat of condensation on the large-scale dynamics of the atmosphere are explicitly included, but the effects of small-scale convective motions are parameterized. As already indicated, a weakness of the model--as is the case with most other models--is that the type and amount of clouds are not computed so that the interaction between cloudiness *changes* resulting from the energy parks and other meteorological fields (especially the radiation field) are not included.

4.2 Scenario of UKMO-IIASA Experiments

The IIASA-UKMO experiments (Murphy et al., 1975) were designed to study the impact of ocean energy parks on simulated climate. The concept of large-scale nuclear energy parks determined the scenarios selected for the experiments. In each experiment there were two energy parks, which each added $1.5 \cdot 10^{14}$ W to the atmosphere. In the first experiment (EX01), the parks were located in the North Atlantic southwest of England and in the North Pacific east of Japan; in the second experiment (EX02), the energy park in the Pacific was in the same location, but the one in the Atlantic was located west of Africa. See Figure 3 for the exact locations of the parks.

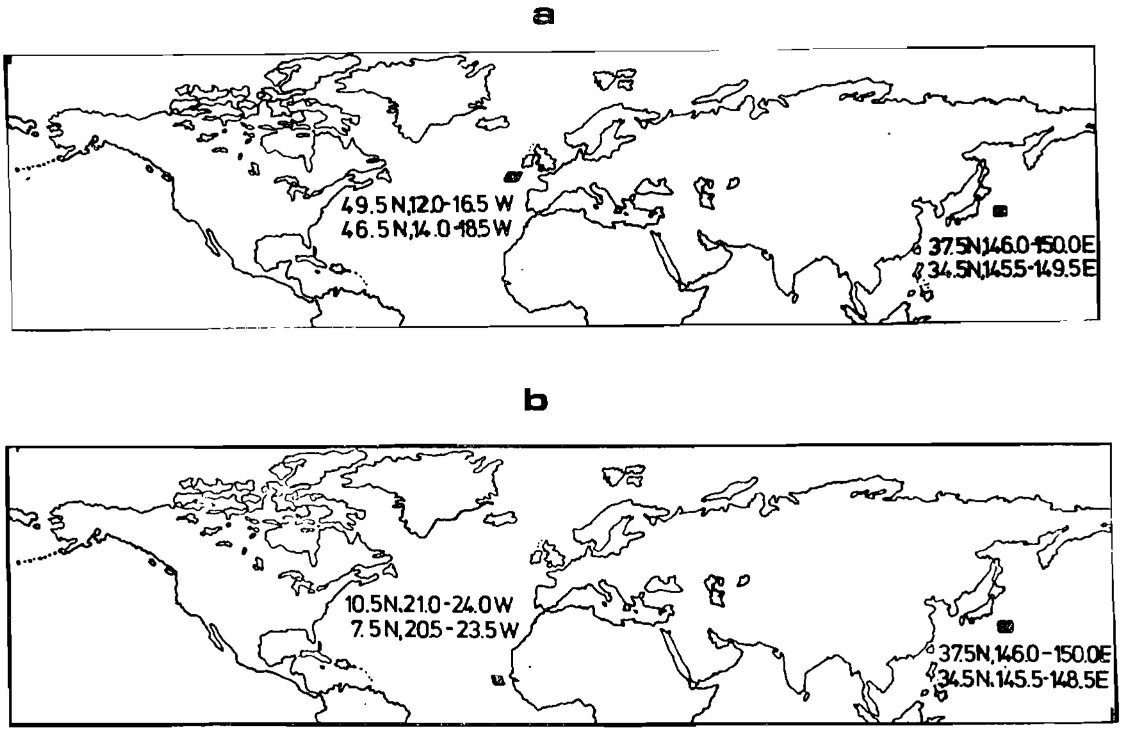


Figure 3. Location of energy parks in (a) EX01 and (b) EX02

The energy parks were not simulated in a completely realistic way because the area of such a park is too small to be properly represented, and because a realistic scenario would involve the spread of the heat by ocean currents and, therefore, would require a linked atmosphere-ocean model. The simplifications introduced were, therefore:

(i) to make the area of a park equal to four grid boxes in the model (see again Figure 2);

(ii) to insert all the heat directly into the atmosphere in sensible form. (Figure 4).

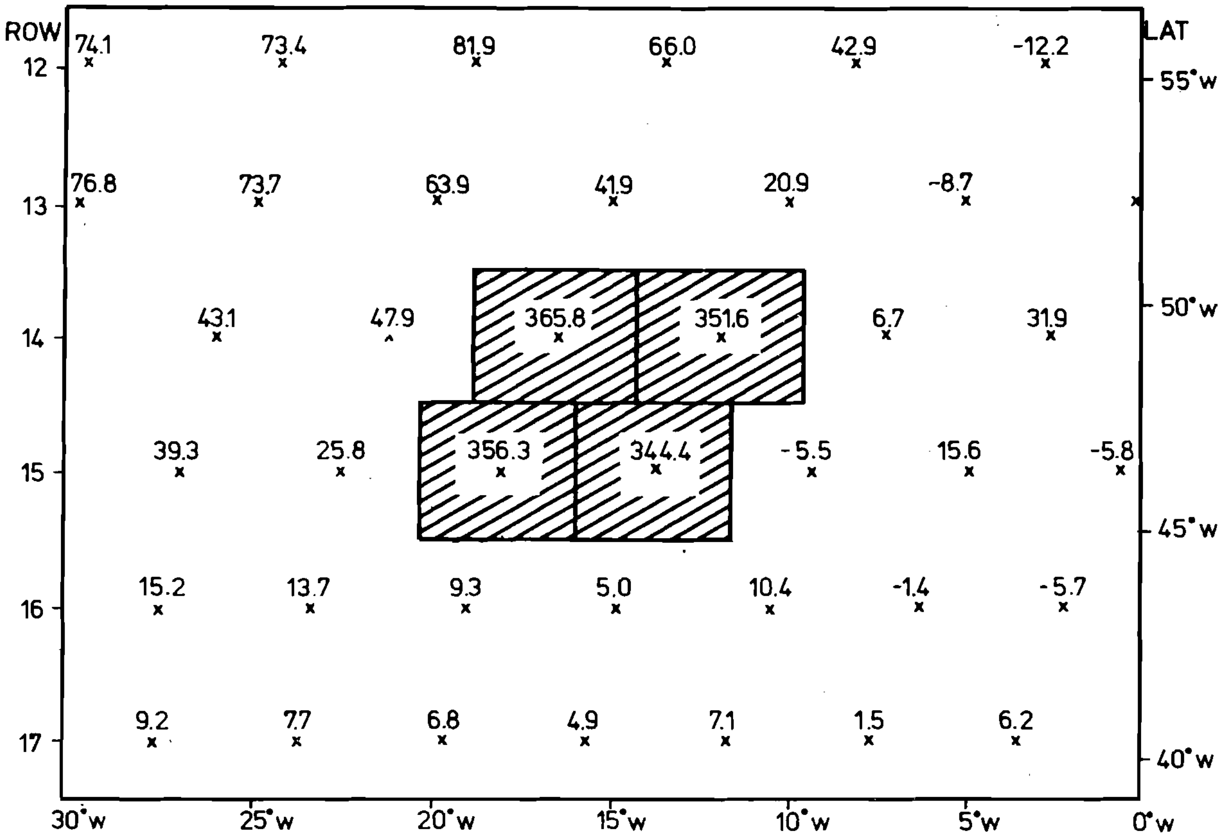


Figure 4. Sensible heat values (in Wm^{-2}) in the vicinity of mid-latitude Atlantic energy park in EX01

To simulate the parks, 375 Wm^{-2} was added to the sensible heat exchange routine of the model (Figure 4). This heat was, therefore, inserted into the lowest layer of the model, which is approximately 200 mb deep. In the quasi-steady state which the model attains after 30 to 40 days, the heat is spread to other parts of the atmosphere; horizontally mainly by wind, and vertically by explicit motion and by the model's convective simulation. The total amount of heat added in the experiments ($3 \cdot 10^{14}$ W) is the same as that added by Washington (1972) based, as described earlier on a per capita energy usage of 15 kW and a population of 20 billion. As Gilchrist (1975a) has pointed out, this total amount of heat is of the same order of magnitude as the heat input in model experiments with sea-surface-temperature anomalies. SSTAs, however, occur over a larger area than the four grid boxes of an energy park. In addition to the energy park experiments, three control cases from the UKMO model were used. These control cases differed from each other only as a result of small random errors in the initial conditions.

5. RESULTS

5.1 Averaging Period

The experiments were performed for a period of 80 days. The model climate came into a quasi-steady state after approximately 40 days. Averages of meteorological variables were taken over the last 40 days (i.e. days 41-80) for further analysis. Figure 5 shows the root-mean-square differences between each energy park experiment and one control case for temperature at $\sigma = 0.5$, as a function of time. The attainment of the quasi-steady state at around 40 days, in terms of differences from the control experiment, is clear.

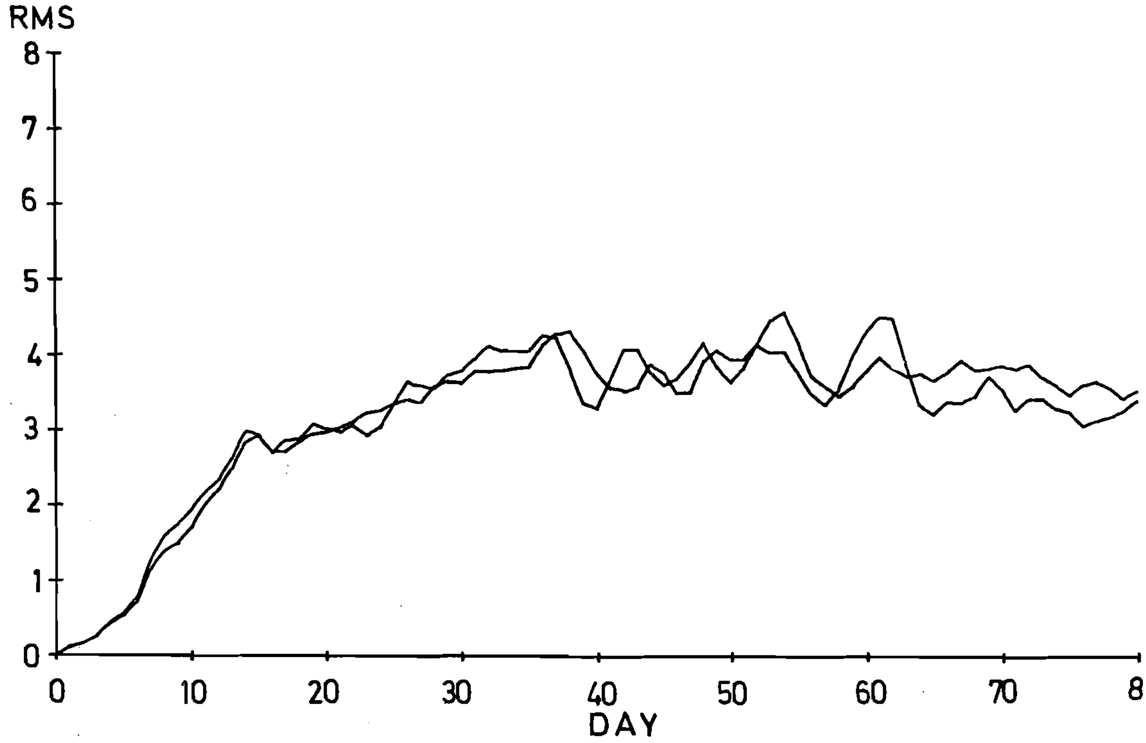


Figure 5. Root-mean-square differences between control case and EX01 and EX02 for temperature at $\sigma = 0.5$, for days 1-80

5.2 Local and Regional Effects

The initial analysis (Murphy et al., 1975; Gilchrist, 1975a) of the energy parks experiments was concerned primarily with the effects of the waste heat in the vicinity of the mid-latitude Atlantic park in EX01. This park gave rise to an atmospheric response on the scale of the park itself which is coherent and exhibits some similarity to the solutions obtained by Smagorinsky (1953) for heat sources on a much larger scale.

For example, there is a surface pressure trough just east of the park, and a ridge to the west; maximum temperatures tend to be observed over the park, so that contour heights at higher levels are brought into phase with the heat input. Figure 6 shows the variations of vertical and meridional velocity, as well as surface pressure and 500 mb height, in a cross-section through the park. Vertical velocities indicate ascending air over and at the downwind edge of the park, with descending air upwind and further downwind of the park. Relative northerlies are found over the park, while relative southerlies occur upwind and downwind of the park.

We have also looked at the effects of the energy parks on rainfall over this area. Rainfall is a variable of great importance because it is particularly sensitive to any changes in atmospheric stability and/or circulation which might be produced by the energy parks. Any large-scale changes in precipitation patterns associated with such waste-heat releases in the future could have important economic and political impacts. However, since rainfall is a more variable parameter it is more difficult to evaluate any effects from a statistical point of view. Figure 7 shows that the precipitation in EX01 is considerably less than that in the control experiments over a large area surrounding and including the park. While these differences were not tested for their statistical significance in this initial analysis, it is of some interest to note that they are consistent with the changes in surface pressure found near the park. It has subsequently been shown that these surface pressure changes are statistically significant. For detailed description of the local impacts see also Gilchrist (1975a).

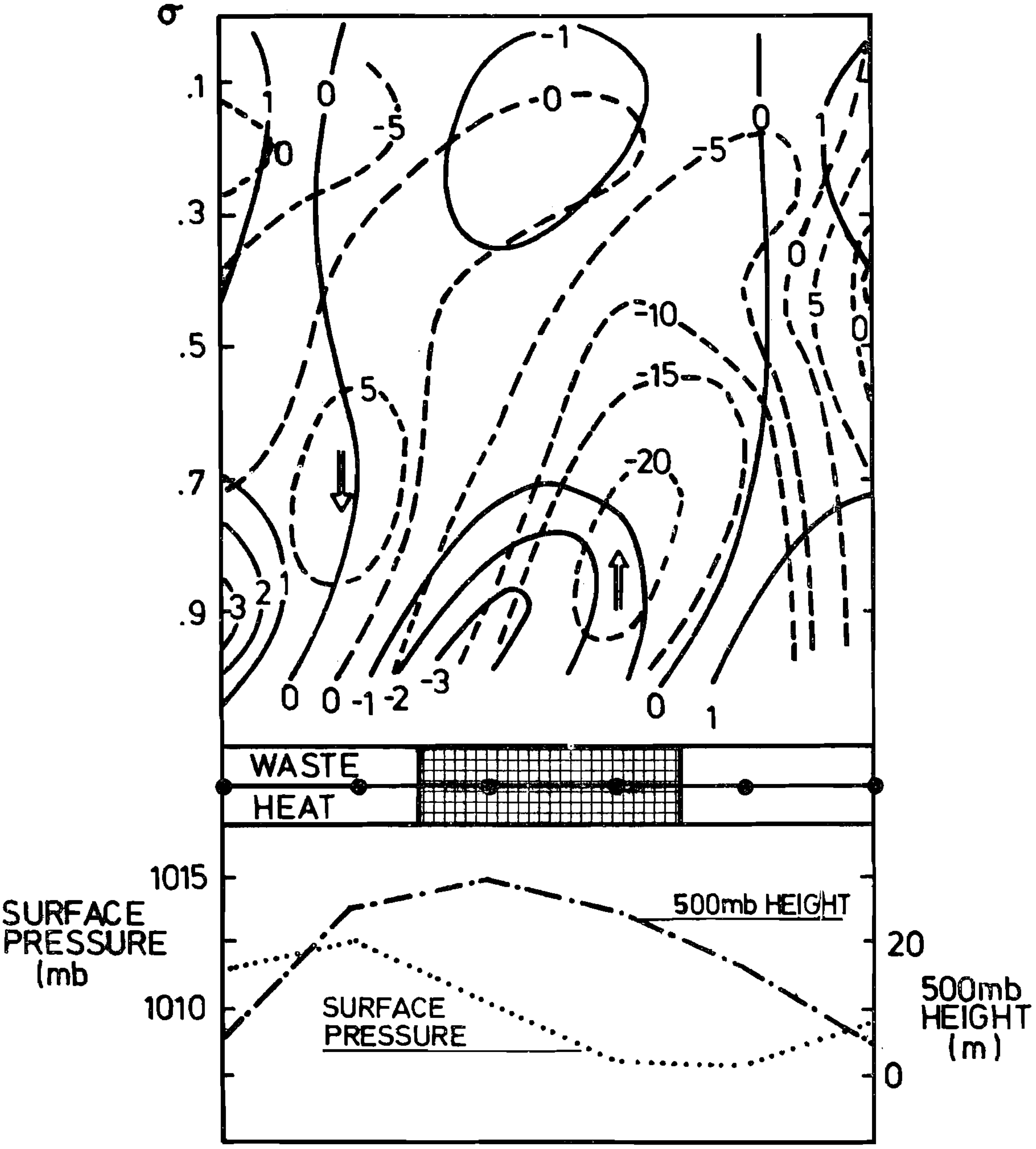


Figure 6.

Values of sea-level pressure (in mb), of 500 mb height (in m) (*bottom*), and of vertical velocity (dashed lines; approximately in mb·hr^{-1}·10), and meridional velocity (solid lines; in m·sec^{-1}) (*top*), across the mid-latitude Atlantic park in EX01. This cross-section consists of six points: two west of the park, two in the park and two east of the park. The linear trend across the park has been removed from the values of 500 mb height and meridional velocity.

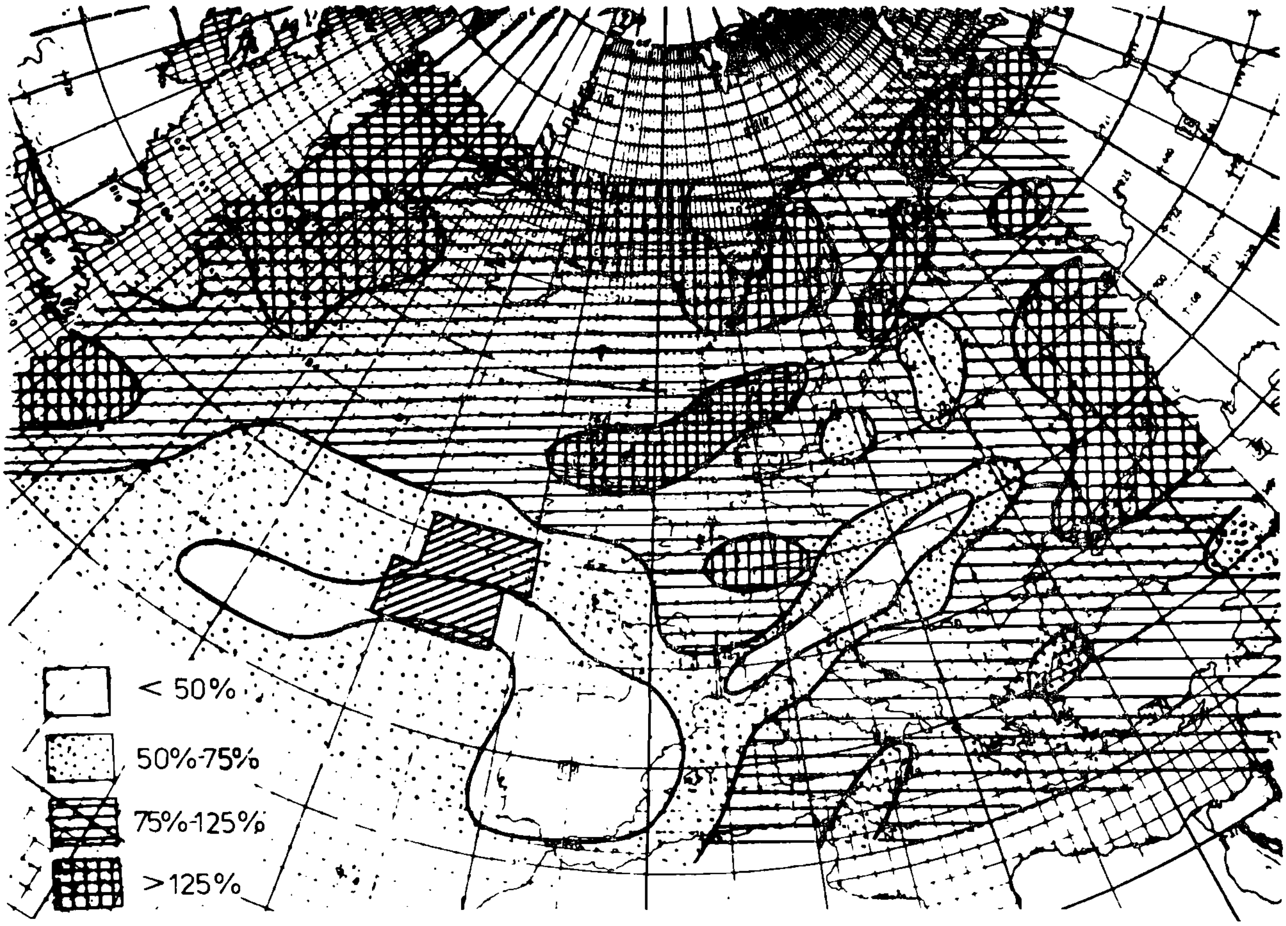


Figure 7. The ratio of precipitation in EX01 to the average precipitation in the four controls over the Western Atlantic and Europe. The stippling designates areas for which this ratio is less than 50%, 50-75%, 75-125%, and greater than 125%.

5.3 Global Impacts

In the first efforts to evaluate the effects of the energy parks, differences between each waste heat experiment and only one control case were calculated. Thus in Häfele et al. (1976) differences for two meteorological variables (Temperature T at $\sigma = 0.5$, and total precipitation) were evaluated between each energy park experiment and only one control case. It is known, however, that a single control case is not representative of the complete model climatology (i.e. the model has an inherent variability); it was, therefore, decided to use three control cases for a better evaluation of the energy parks experiments, and differences were taken between the anomaly cases and an average of the three control cases.

Figure 8 illustrates the difference in surface pressure p_* between EX01 and the average of the control cases (Figure 8a), and between EX02 and the average of the control cases (Figure 8b). The locations of the energy parks are marked there. It is immediately apparent that more areas than only those over the

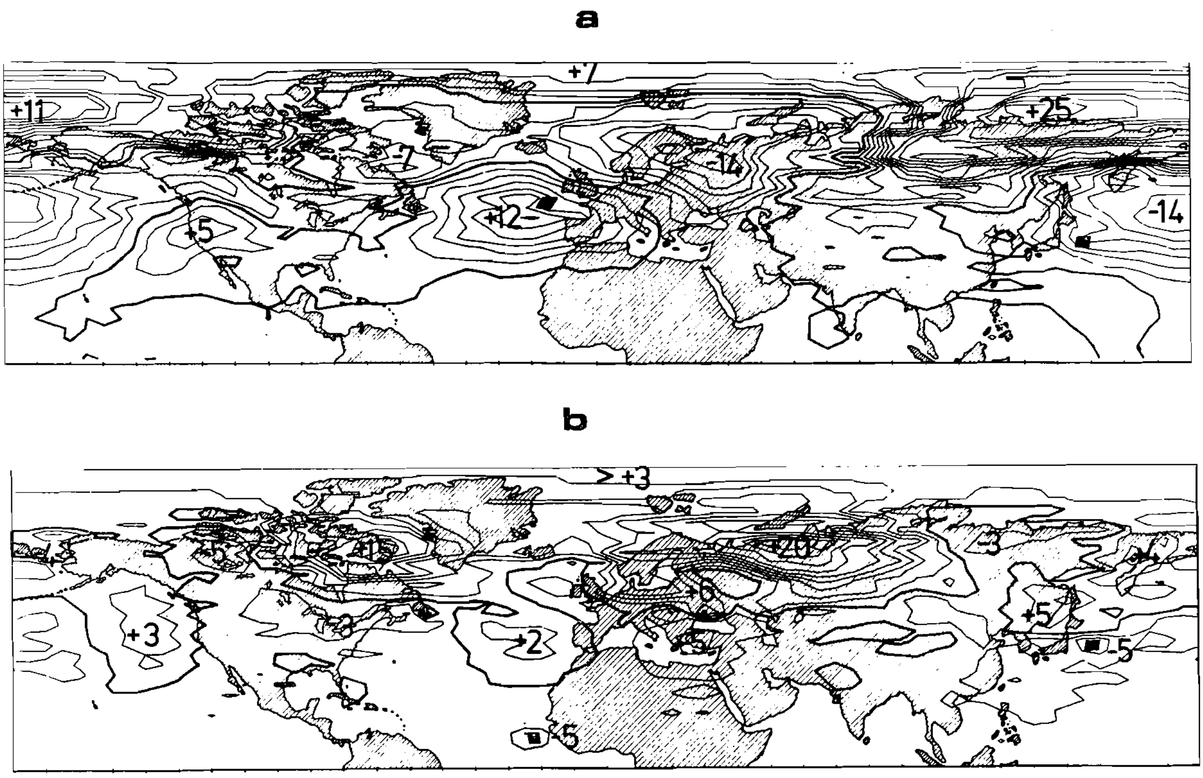


Figure 8. The differences in 40-day mean surface pressure (in mb) between *(a)* EX01 and *(b)* EX02 and the average of the three control experiments. (Contours at every 2 mb, heavy lines at 0 mb.)

energy parks experienced a change in surface pressure. It is also clear that the changes in EX01 were of greater magnitude than those in EX02. In both cases, pressure changes occurred over large coherent areas in the extratropical latitudes, with not such a large change (if any) in tropical latitudes. In EX01, the surface pressure increased (by up to 12 mb) over and upstream and downstream from the Atlantic energy park, while it decreased over and downstream from the Pacific park. Over north-western Europe the surface pressure was reduced by up to 14 mb, while in Arctic USSR there was an increase of 25 mb. Over North America the changes were not so large, with an increase of 5 mb over the western United States and a decrease of 7 mb over the eastern Canadian Arctic.

In EX02, the largest changes in surface pressure occurred over western Europe and the USSR (increase of up to 20 mb) and over the eastern Canadian Arctic (increase of up to 15 mb). As in EX01, the Pacific energy park experienced a decrease of surface pressure. The Atlantic energy park, which in EX02 is in the tropical Atlantic, does not have a large change of pressure over it or upstream and downstream. Quite large differences between Figures 8a and 8b should be noted. For instance, over western Europe a large pressure decrease was observed in EX01 while an increase occurred in EX02. Over eastern Siberia a large pressure increase occurs in EX01 but in EX02 there is relatively little change.

It is clear from consideration of Figure 8 that the location of two energy parks in the extratropical latitudes has influenced the surface distribution more than if the Atlantic energy park is placed in the tropics. The Atlantic energy park in EX01 is in an area where the atmosphere is basically stable with, normally, small heat exchange values; so virtually all of the waste heat input is effective, because it is a true additional heat source and the response of the model is not such as to reduce its amount significantly. In contrast, in the tropical Atlantic the model atmosphere stability can change and thereby reduce the impact of the energy input from the park. In the Pacific, in both energy park experiments, the pressure falls in an area which normally has low pressure, i.e. the trough is deepened by the energy input.

Figure 9 shows the differences in temperature at $\sigma = 0.9$ for days 41-80 between EX01 and the average of the three control cases (Figure 9a), and between EX02 and the average of the three control cases (Figure 9b). As with the pressure distributions, we see that the temperatures have been changed over large coherent areas of the hemisphere, not just over the energy parks themselves. Over the energy parks the temperatures have increased by up to 5^{0}C.

In EX01, the largest temperature changes occurred over areas of western Europe and of the USSR (increase up to 11^{0}C), over the Canadian Arctic (temperature decrease of up to 9 C), and over Kamchatka (11^{0}C increase). Other areas show increases of up to 6^{0}C. It is possible to relate these temperature changes to the pressure changes. For example, the pressure distribution over western Europe (a large decrease centred just east of Scandinavia) implies increased westerly winds and penetration of cyclones over the area, which in January would be associated with a warming. Likewise, the large increase of pressure over eastern Siberia implies increased anticyclonicity over the area and this is associated with decreasing temperatures.

In EX02, the temperature changes are not quite as large in amplitude. Nevertheless, a decrease of 13^{0}C is seen over central Europe with decreases of up to 9^{0}C over the rest of Europe and the USSR. Over North America the temperature decreased in EX02 as it did in EX01, but by only 3^{0}C. The main difference between Figures 9a and 9b is, therefore, the temperature change over Europe and the USSR, and this is consistent with the difference in the pressure changes observed over the same area.

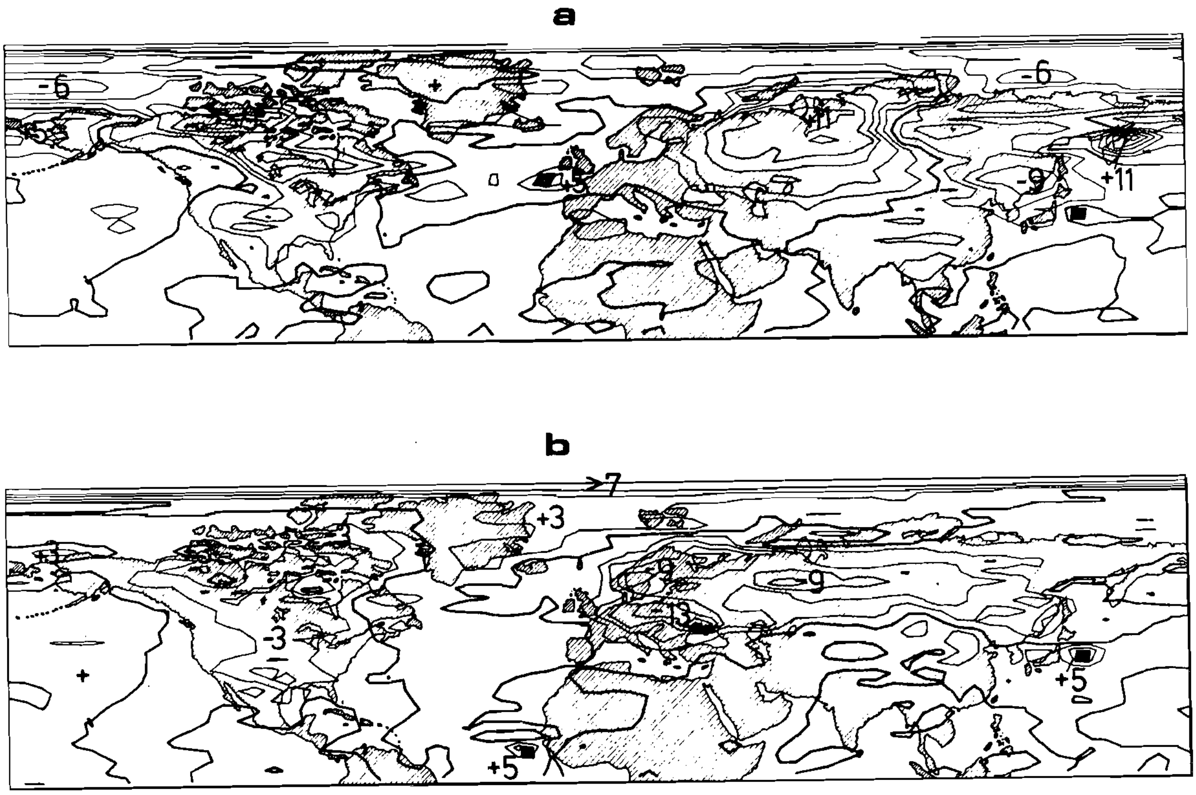


Figure 9. The differences in 40-day mean temperature (in ^{0}C) in the lowest layer of the model between experiments *(a)* EX01 and *(b)* EX02 and the average of the three control experiments. (Contours at every 2^{0}C, heavy lines at 0^{0}C.)

The differences in total precipitation for days 41-80 are shown in Figure 10a for EX01, and the average of the three controls in Figure 10b for EX02. In both cases, the largest changes occur in the tropics. In EX01, the largest precipitation change is over Indonesia (increase of 19 mm per day), with other large changes near Central America, the Indian Ocean, and the Pacific Ocean. Over the energy parks in EX01 the changes in total precipitation are not so large. In EX02, the largest precipitation change is over the tropical Atlantic energy park (increase of 32 mm per day), with other large changes over the Indian and tropical Pacific oceans. It is clear that the total precipitation is locally influenced by an energy park only when the park is in the tropical ocean. It may also be

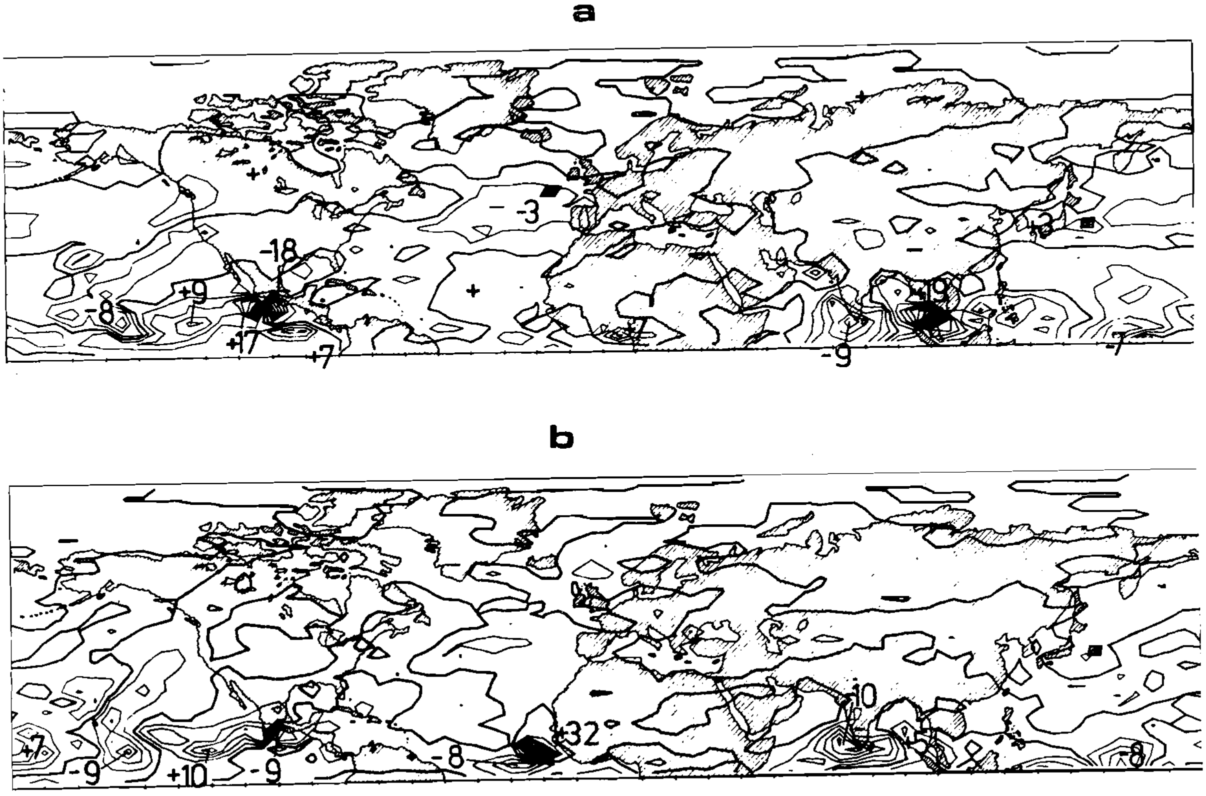


Figure 10. The differences in 40-day mean total precipitation (in mm/day) between experiments *(a)* EX01 and *(b)* EX02 and the average of three control experiments. (Contours at every 2 mm/day, heavy lines at 0 mm/day.)

concluded that the energy parks induce total precipitation changes primarily over tropical ocean areas, not over tropical land or extratropical land and ocean areas.

Consideration of Figures 8, 9, and 10, therefore, shows that the input of waste heat at two energy parks has affected pressure, temperature, and rainfall not only locally but over the hemisphere as a whole. It is interesting to note that GCM experiments with sea-surface temperature anomalies have generally shown that anomalies in the tropical oceans have more impact than those in mid-latitudes, while the energy parks experiments have suggested that if both parks are in mid-latitudes the effect is greater than if one of them is moved to a tropical ocean location.

As pointed out in an earlier section, however, it is important to make a further evaluation of the differences described above, in order to find out how much of the difference between an experiment and the control cases is due to the model's inherent variability (or noise level), and how much is due to the inclusion of the energy parks (or signal).

The significance of the differences can be computed by calculating the ratio r of the absolute value of the differences to the standard deviation of the variable in the three control experiments. That is, for each grid point and for any variable (temperature, for example) we can compute:

$$r = \frac{x_p - x_c}{s_{xc}}$$

where

x_p is the 40 day mean value of the variable in the energy park experiment;

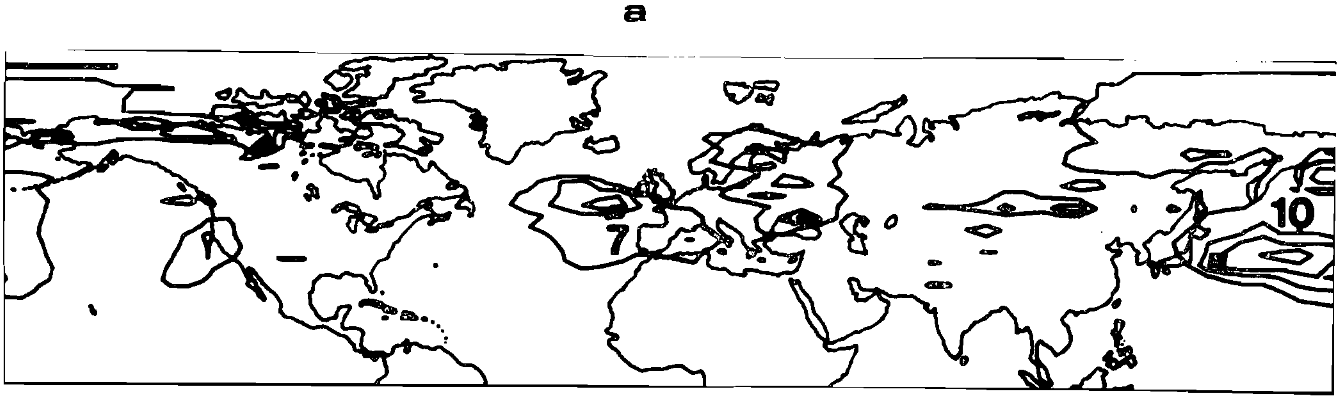
x_c is the 40 day mean value of the variable for the average of the three controls;

s_{xc} is the standard deviation of the 40 day mean values of x between the three control cases.

Ratio r has a student's t distribution with two degrees of freedom (assuming that the values of x in the experiments are independent and normally distributed). Values of a ratio greater than 4.30 are statistically significant at the 0.05 level (two-sided test). That is, if the ratio r for the variable under consideration is greater than 4.30 at a particular grid-point, there is a 95% chance that the difference between the energy park experiment and the average of the controls is due to a response to the energy park and not to the inherent variability of the model.

Figure 11 shows the values of this ratio for surface pressure p_* for EX01 (Figure 11a) and EX02 (Figure 11b). An examination of the standard deviation of p_* (see Figure 12) for the three control cases shows that the values were smaller than those observed for the real atmosphere. For the computation of the ratios shown in Figure 11, a minimum value of s_{p_*c} of 1 mb has been taken, i.e. if s_{p_*c} is less than 1 mb it has been replaced by $s_{p_*c} = 1$ mb in the computation of r.

The values of the ratios, therefore, show that many of the pressure changes noted earlier can be ascribed to the noise level of the model. For EX01, the surface pressure changes in the vicinity of the energy parks can be ascribed to the influence of the parks. The large surface pressure decrease over western



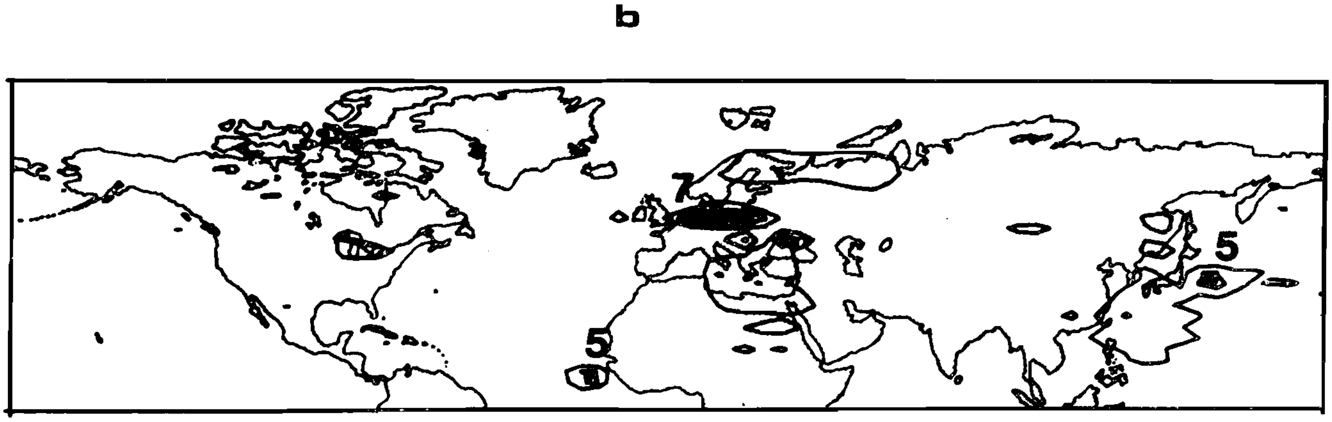


Figure 11. The ratio of the absolute value of the differences in surface pressure to the standard deviation of that variable in the three control experiments for *(a)* EX01 and *(b)* EX02. (Contour interval 2 units.)

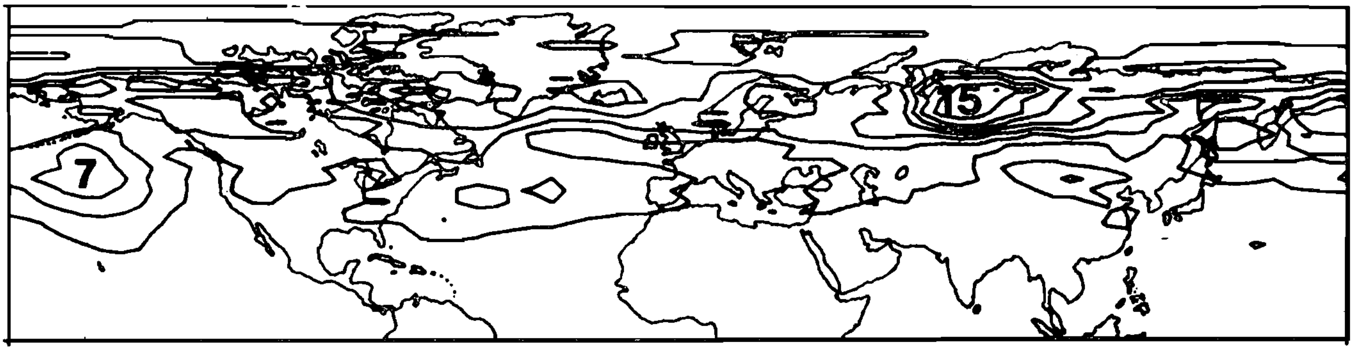


Figure 12. Standard deviation of 40-day mean values of surface pressure (in mb) in the three control cases. (Contour interval 2 units.)

Europe (Figure 11a), however, occurs in an area where the model variability is high, so that the change is not significantly associated with the introduction of the parks. For EX02, the surface pressure changes are only significantly related to the introduction of the parks in the vicinity of the parks themselves and in one area of western Europe. Elsewhere, the surface pressure changes observed in Figure 11b are more likely to be due to model variability.

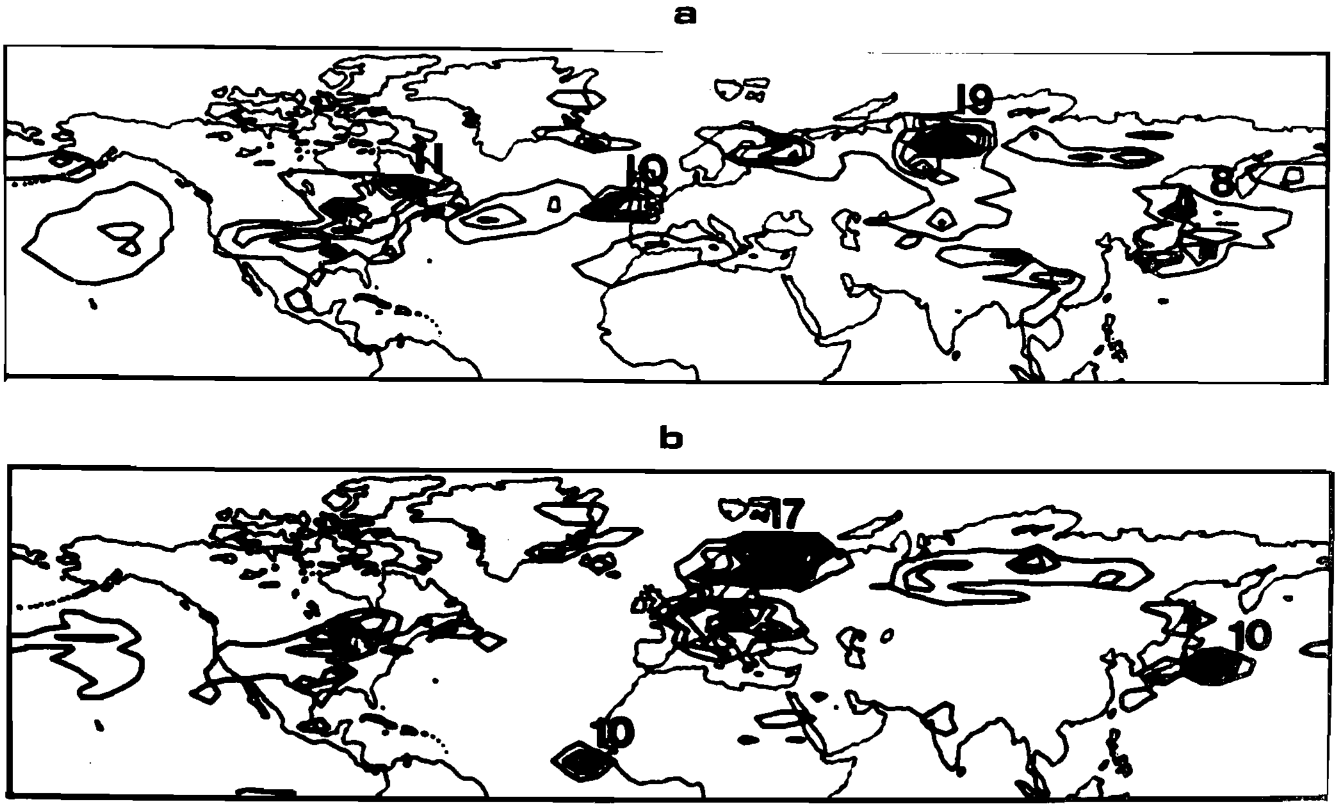


Figure 13. The ratio of the absolute value of the differences in temperature at $\sigma = 0.9$ to the standard deviation of that variable in the three control experiments for *(a)* EX01 and *(b)* EX02. (Contour interval 2 units.)

The values of the ratios for T at $\sigma = 0.9$ are shown in Figure 13a for EX01 and Figure 13b for EX02. It is not surprising that the temperature changes in the vicinity of the energy parks in both experiments are statistically significant. In both experiments, however, significant temperature changes have occurred over other regions of the hemisphere. In EX01, there are significant changes over eastern Canada, northern Siberia, the western Atlantic region and north eastern USSR. In EX02, significant changes are seen over North America (particularly over the Great Lakes region), Europe and Siberia.

The values of the ratios for total precipitation are shown in Figure 14. The precipitation changes in the vicinity of the Atlantic energy parks are found to be significant, while the changes over the Pacific park can be ascribed to model variability. In both experiments most of the significant changes in precipitation occur in the tropics, the only exception being in EX01, where there is a significant change over the mid-Atlantic and Spain in association with the Atlantic energy park.

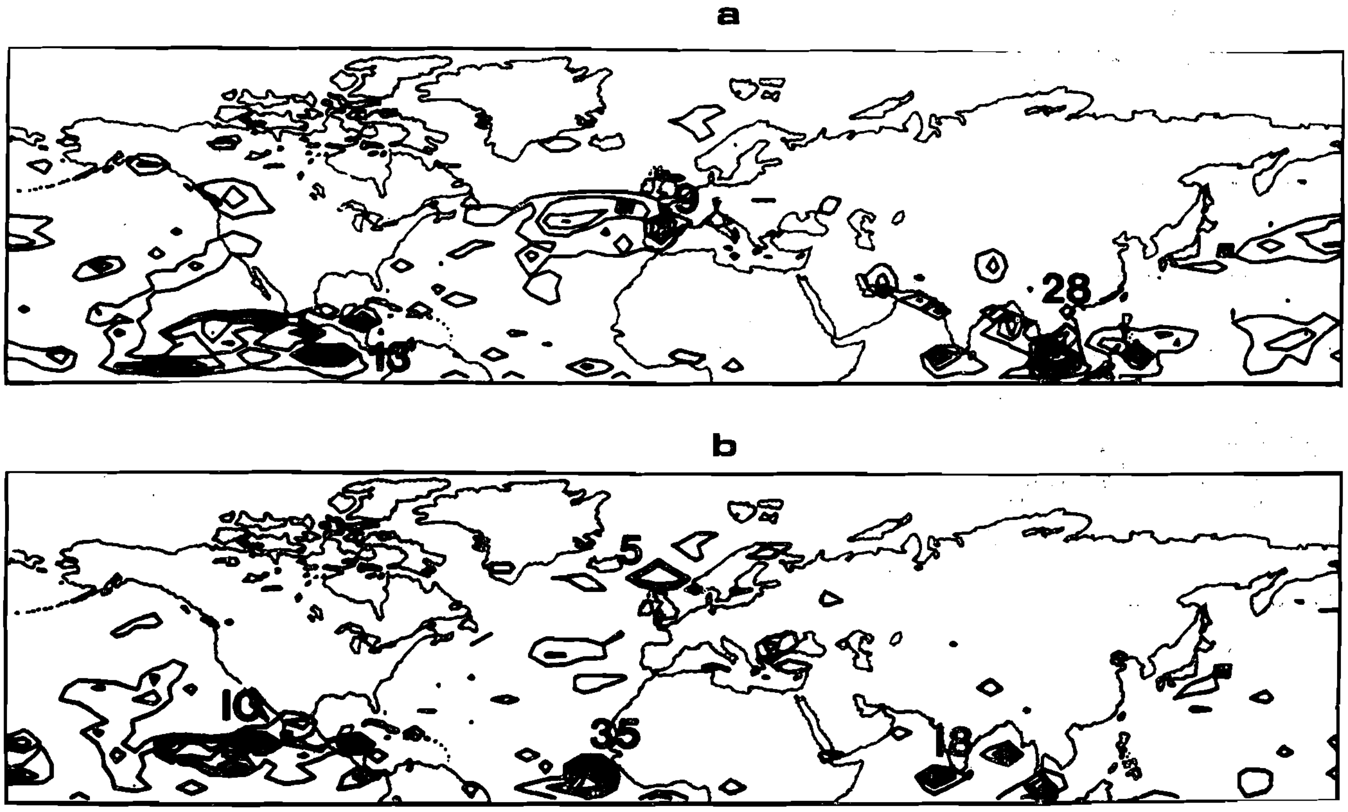


Figure 14. The ratio of the absolute value of the differences in total precipitation at $\sigma = 0.9$ to the standard deviation of that variable in the three control experiments for *(a)* EX01 and *(b)* EX02. (Contour interval 2 units.)

The large values of the ratio are distributed in somewhat random fashion in the tropics. It should be noted that, despite their size, these values are probably not significant because rainfall in the tropics arises primarily as a result of local instabilities. There is a tendency for rain, once initiated at a grid point, to persist as a result of small-scale dynamical interactions. This is particularly so near the equator in a hemispheric model. Because of this, the distribution of daily rainfall amounts is highly skewed; consequently, even for 40-day means, the assumption of normality, which is required for the application of significance tests to the t-statistic, probably does not hold. Therefore, values which are apparently significant occur by chance.

6. CONCLUSIONS

It was concluded in the past (e.g. SCEP, 1970) that thermal pollution would not affect global climate because the amount of waste heat would represent only a very small fraction of the amount of solar radiation incident upon the globe. But as Singer (1975) has pointed out, it is a mistake to assume that the energy input from human activities can be neglected just because the average heat input is so much less than the solar heat input. The heat input is bound to be localized, and since the climate system is very complex energy inputs in particular places could trigger a series of changes in components of the climate system.

Numerical models of the atmospheric circulation represent the best method available at present for investigating the impacts of waste heat, since they do include many of the non-linear interactions in the climate system which could be of importance if thermal pollution has an effect on climate.

Model experiments in which sea-surface temperature anomalies were introduced have shown that global (or hemispheric) changes can result from anomalies in tropical sea-surface temperatures and very large anomalies in mid-latitude sea-surface temperatures. Further model experiments in which thermal pollution was introduced in continental areas showed that the simulated atmospheric circulation responded on a global scale to unrealistically large heat inputs, but only on a local scale to a more realistic level of thermal pollution.

The IIASA-UKMO model experiments have investigated the response of the simulated northern hemisphere circulation to ocean energy parks, in which a total of $1.5 \cdot 10^{14}$ W was introduced into the atmosphere at each of two energy parks, one in the Atlantic Ocen and one in the Pacific Ocean. Results showed that the simulated atmospheric circulation is changed in the vicinity of the parks and elsewhere in the hemisphere. It appears that the combination of two extratropical energy parks has more impact on the simulated circulation than a combination involving a tropical Atlantic energy park.

It is not valid to assume that the atmosphere would respond in exactly the same way as the model to the introduction of energy parks, but we must recognize that the results of these model experiments indicate a possible atmospheric response, which must be borne in mind for planning purposes and also investigated further.

On the basis of the results of the first two energy parks experiments, further experiments will be made at IIASA with the UKMO model to investigate the response of the simulated atmosphere to energy parks. One experiment will study the impact of only one energy park, of the same magnitude as before and located in the extratropical Atlantic. In a second experiment, the response to two extratropical energy parks will be evaluated, involving only half the amount of heat used in the earlier experiments. A third experiment is designed to study a more realistic heat input; there the waste heat will be transferred to a mixed-layer ocean-box model below the energy parks, so that the energy can then be used to heat up the ocean layer and be released into the atmosphere in the form of sensible and latent heat.

ACKNOWLEDGMENT

We would like to thank Ruth Kuhn of the Kernforschungszentrum Karlsruhe for her great efforts in supervising the running of the model.

References

Arakawa, A. (1975), General Circulation of the Atmosphere, *Rev. Geophys. Space Phys.*, 13, 668-799.

Bjerknes, J. (1969), Atmospheric Teleconnections from the Equatorial Pacific, *Mon. Weather Rev.*, 97, 163-172.

Chervin, R.M., W.M. Washington, and S.H. Schneider (1976), Testing the Statistical Significance of the Response of the NCAR General Circulation Model to North Pacific Ocean Surface Temperature Anomalies, *J. Atmos. Sci.*, 33, 413-423.

Corby, G.A., A. Gilchrist, and R.L. Newson (1972), A General Circulation Model of the Atmosphere Suitable for Long Period Integrations, *J. R. Meteorol. Soc.*, 98, 809-832.

Egger, J. (1976), *The Impact of Waste Heat on the General Circulation: Experiments with a Three-dimensional Statistical-dynamical model.* Meteorologisches Institut der Universität München, Munich, FRG, to be published.

GARP (1975), The Physical Basis of Climate and Climate Modelling, *GARP Publications Series, No. 16*, World Meteorological Organization, Geneva.

Gilchrist, A. (1975a), *Some Results from the UK Meteorological Office Model Relevant to the Waste Heat Experiments*, paper presented at IIASA Energy and Climate Meeting, April 29-30, 1975, and Met 020 Technical Note II/59, UK Meteorological Office, Bracknell, UK.

Gilchrist, A. (1975b), *The Influence of Atlantic Ocean Sea Surface Temperatures on West African Rainfall*, Met 020 Technical Note II/50, UK Meteorological Office, Bracknell, UK.

Häfele, W. (1974), A Systems Approach to Energy, *Am. Sci.*, 62, 438-447.

Häfele, W. et al. (1976), Second Status Report of the IIASA Project on Energy Systems, 1975, RR-76-1, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Houghton, D.D., J.E. Kutzbach, M. McClintock, and D. Suchman (1974), Response of a General Circulation Model to a Sea-Temperature Perturbation. *J. Atmos. Sci.*, 31, 857-868.

Kellogg, W.W., and S.H. Schneider (1974), Climate Stabilization for Better or for Worse? *Science*, 186, 1163-1172.

Lamb, H.H. (1972), *Climate: Present, Past and Future, Volume I, Fundamentals and Climate Now*, Methuen and Co. Ltd., London.

Llewellyn, R.A., and W.M. Washington (1976), Regional and Global Aspects, in *Energy and Climate: Outer Limits to Growth*, G1-G38, Geophysics Study Committee, National Research Council, Washington, DC.

Manabe, S. and K. Bryan (1969), Climate Calculations with a Combined Ocean-Atmosphere Model, *J. Atmos. Sci.*, 26, 786-789.

Mason, B.J. (1976), Towards the Understanding and Prediction of Climate Variations, *Q. J. R. Meteorol. Soc.*, 102, 473-498.

Murphy, A.G., A. Gilchrist, and W. Häfele (1975), *Impact of Waste Heat on Climate: Preliminary Results of Some Numerical Experiments*, paper presented at WMO/IAMAP Symposium on Long-Term Climatic Fluctuations, August 18-23, 1975, Norwich, UK.

Penner, S.S. (1976), *Monitoring the Global Climatic Impact of Direct Heat Addition Associated with Escalating Energy Use*, paper presented at AIAA 9th Fluid and Plasma Dynamics Conference, San Diego, Calif., July 15, 1976.

Rowntree, P.R. (1972), The Influence of Tropical East Pacific Ocean Temperature on the Atmosphere, *Q. J. R. Meteorol. Soc.*, 98, 290-321.

Rowntree, P.R. (1976), Response of the Atmosphere to a Tropical Atlantic Ocean Temperature Anomaly, *Q. J. R. Meteorol. Soc.*, 102, 607-626.

SCEP (1970), *Man's Impact on the Global Environment*, The MIT Press, Cambridge, Mass.

Schneider, S.H., and R.D. Dennett (1975), Climatic Barriers to Long-term Energy Growth, *Ambio*, 4, 65-74.

Schneider, S.H., and R.E. Dickinson (1974), Climate Modeling, *Rev. Geophys. Space Phys.*, 12, 447-493.

Shukla, J. (1975), Effect of Arabian Sea-Surface Temperature Anomaly on Indian Summer Monsoon: a Numerical Experiment with the GFDL Model, *J. Atmos. Sci.*, 32, 503,511.

Singer, S.F. (1975), Environmental Effects of Energy Production, in S.F. Singer, ed., *The Changing Global Environment*, D. Reidel Publishing Company, Dordrecht, Netherlands, 25-44.

Smagorinsky, J. (1953), The Dynamical Influence of Large-scale Heat Sources and Sinks on the Quasi-stationary Mean Motions of the Atmosphere, *Q. J. R. Meteorol. Soc.*, 79, 342-366.

Smagorinsky, J. (1974), Global Atmospheric Modeling and the Numerical Simulation of Climate, in W.N. Hess, ed., *Weather and Climate Modification*, Wiley and Sons, New York, 632-686.

SMIC (1971), *Inadvertent Climate Modification, Report of the Study of Man's Impact on Climate*, The MIT Press, Cambridge, Mass.

Spar, J. (1973a), Supplementary Notes on Sea-Surface Temperature Anomalies and Model-generated Meteorological Histories, *Mon. Weather Rev.*, 101, 767-773.

Spar, J. (1973b), Transequatorial Effects of Sea-surface Temperature Anomalies in a Global General Circulation Model, *Mon. Weather Rev.*, 101, 554-563.

Spar, J. (1973c), Some Effects of Surface Anomalies in a Global General Circulation Model, *Mon. Weather Rev.*, 101, 91-100.

US Committee for the Global Atmospheric Research Program (1975), *Understanding Climatic Change*, National Academy of Sciences, Washington, DC.

Washington, W.M. (1971), On the Possible Uses of Global Atmospheric Models for the Study of Air and Thermal Pollution, in W.H. Matthews et al., eds., *Man's Impact on the Climate*, The MIT Press, Cambridge, Mass.

Washington, W.M. (1972), Numerical Climatic Change Experiments: The Effect of Man's Production of Thermal Energy, *J. Appl. Meteorol.*, 11, 763-772.

Weinberg, A.M., and R.P. Hammond (1970), Limits to the Use of Energy, *Am. Sci.*, 58, 412-418.

Weinberg, A.M., and R.P. Hammond (1971), Global Effects of Increased Use of Energy, *Proceedings of the Fourth United Nations International Conference on the Peaceful Uses of Atomic Energy*, Geneva, September 6-16, 1971, 1, 171, United Nations, New York, and International Atomic Energy Agency, Vienna.

Wetherald, R.T., and Manabe, S. (1972), Response of the Joint OceanOcean-Atmosphere Model to the Seasonal Variation of the Solar Radiation, *Mon. Weather Rev.*, 100, 42-59.